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Strengthening mechanisms in cement-stabilised rammed earth

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ABSTRACT: There is currently little scientific understanding of stabilised rammed earth (RE) and the relationship between water-cement ratio and compressive strength. For traditional (unstabilised) RE materials, it is standard practice to compact the soil mix at its optimum water content to achieve maximum dry density and hence maximum strength. However, this may not also apply to cement-stabilised rammed earth (CSRE). A recent investigation (Beckett and Ciancio 2014) showed that CSRE samples stabilised with 5% cement and compacted at a water content lower than optimum performed better than samples compacted at optimum or higher. This seems to be in agreement with the well-known effect in concrete materials, according to which the lower the water-cement ratio, the stronger the cementitious products hence the higher the compressive strength. This paper investigates the effect of water cement ratio in CSRE samples. Results of an experimental programme are presented and used to discuss the appropriateness of the water-cement ratio for RE materials.

1 INTRODUCTION

Cement stabilisation is now commonplace in rammed earth (CSRE) construction. Although it has been acknowledged by several authors that there is a significant reduction in its environmental sustainability (e.g. Venkatarama Reddy and Prasanna Kumar 2010), the associated increase in material strength and durability is undeniable. However, what is less clear is how best to control the effects of cement stabilisation to achieve the maximum material improvement for the least cost, both environmental and financial.

Venkatarama Reddy and Prasana Kumar (2011a, 2011b) investigated several aspects of CSRE construction. For all of the materials tested, an increase in unconfined compressive strength (UCS) was found with compaction water contents increasing from below to above the optimum water content (OWC). Similarly, materials compacted at a given water content but to a range of dry densities (ρ_d) also showed increasing UCS with increasing ρ_d. Water content at testing was also examined; specimens dried at 50°C showed significantly higher UCS than similar specimens which had been dried and then submerged in water for 48 hours. This result is consistent with those found by Jaquin et al. 2009, and later Bui et al. 2014, for unstabilised RE, who demonstrated the strong link between suction present in RE's water phase and material strength. This suggests that suction phenomena also play a key role in CSRE.

Cement hydration mechanisms in CSRE were investigated by Beckett and Ciancio 2014. In that work, wrapped specimens were used to determine amounts of water used in cement hydration for specimens compacted above, at and below their OWC. Specimens with lower compaction water contents were found to have higher UCSs for all tested hydration times (between 1 and 28 days), contrary to findings in Venkatarama Reddy and Prasanna Kumar 2011a. Somewhat counter-intuitively, these specimens also had marginally lower dry densities than the other specimens tested and contained the least amount of hydrated cement. It was suggested that specimen strengths were therefore dependent on cement distribution and a transition between 'bridge' and 'matrix'-dominated cement regimes as compaction water contents increased.

It is clear from these works (and numerous others that cannot be covered here) that the interaction between cement, water and soil in CSRE is far more complicated than it has been credited with in the past. This paper presents an experimental investigation in which compaction water content, dry density and cement contents are closely controlled in order to more clearly discern the effects of each component on subsequent material strengths. Details of the experimental programme are given in the following section, after which results are presented and discussed in the light

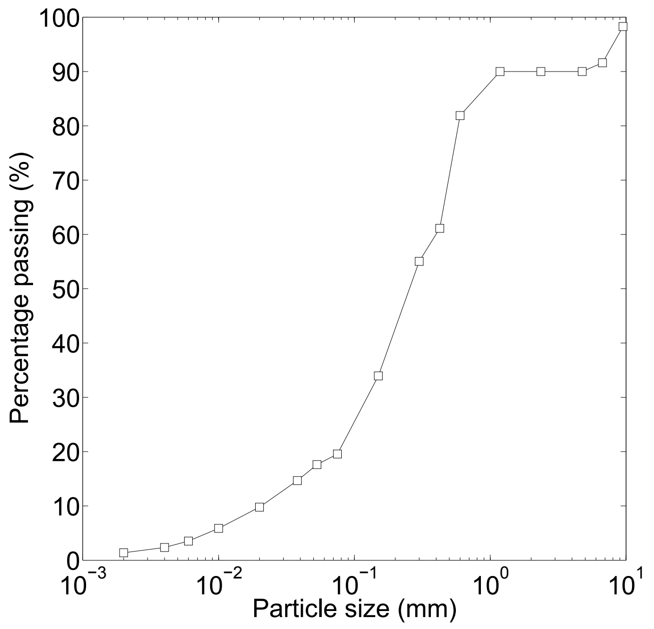

Figure 1: Particle grading curve for engineered soil mix

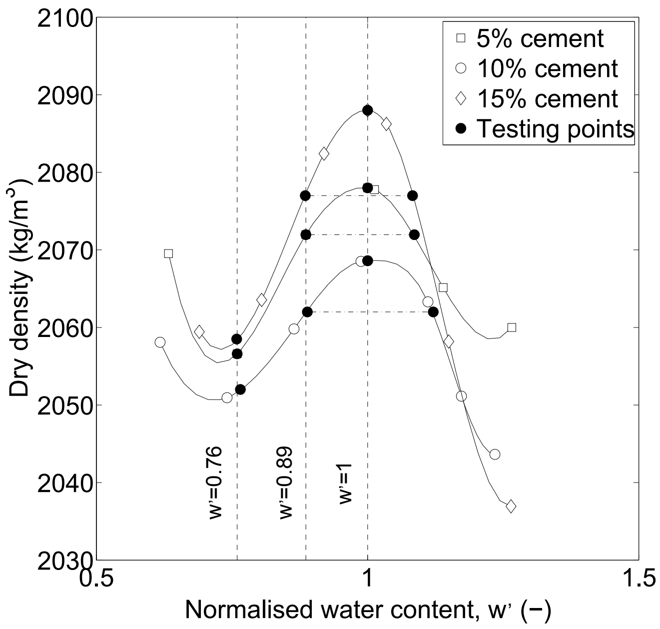

Figure 2: Normalised compaction curves for the three tested stabiliser contents

of those found by previous authors.

2 EXPERIMENTAL PROGRAMME

2.1 *Material*

An engineered soil, manufactured from controlled quantities of silt (Unimin Silica 200G), sand (an equal mix of Unimin SF and RC sand) and blue metal aggregate (max size 10mm) was selected for testing. Clay was not added to the mix as it has been shown to interfere with cement hydration; although this would be more representative of the behaviour of stabilised natural soils, clay was omitted for improved experimental consistency. The particle size distribution for the final mix is shown in Figure 1. Cement contents of 5, 10 and 15% were selected for testing to represent typical stabiliser quantities used in RE construction and added to the dry soil mix. To improve consistency, specimens were manufactured from individual batches of each mix.

2.2 *Compaction water contents and specimen manufacture*

CSRE OWCs were determined using the Modified Proctor test as per AS 1289.5.2.1 (Standards Australia 2003). Water was added to dry soil and cement mixes in *a priori* known amounts and mixed for 5 minutes to ensure, as far as practicable, uniform water distributions throughout the material. Wetted mixes were compacted within 45 minutes of water addition. Compaction curves for each mix are shown in Figure 2, where compaction water content, w, has been normalised via $w' = {}^{w}/\text{owc}$. OWCs for 5, 10 and 15% cement stabilised mixes were 7.9, 8.1 and 8.7% (by mass) respectively. Four values of w' were then chosen for specimen manufacture as shown in Figure 2: $w' = 0.76$ and $w' = 0.89$ (corresponding to measured datapoints for 5% cement content), selected to determine whether an optimum strength existed for materials compacted <OWC, as found in Beckett and Ciancio 2014; $w' = 1$ to investigate behaviour of specimens compacted to their maximum dry density ($\rho_{d,max}$); and $w' > 1$, corresponding to ρ_d values equal to those at $w' = 0.89$ for that mix. Interestingly, Figure 2 shows that the compaction curve for 10% cement falls below those of 5 and 15% for all but the highest values of w'. This is contrary to results found by Bryan 1988 and later by Venkatarama Reddy and Prasanna Kumar 2011a, who found either unchanging or increasing $\rho_{d,max}$ with increasing cement content and serves to highlight the variability inherent in earthen materials.

∅100mm, 200mm tall UCS specimens were compacted in five equal layers of controlled mass and volume to ensure correct compacted densities. Once compacted, specimens were removed from the mould and cured under conditions of 94±2% humidity, 21±1°C for 28 days to ensure suction equilibration. Specimen UCS was then immediately determined by uniaxial crushing at a rate of 0.3mm/min until failure, preventing re-equilibration to atmospheric conditions. Crushed material was oven-dried for 24 hours at 105°C to determine its free water content and ρ_d.

3 EXPERIMENTAL RESULTS

Figure 3 shows results for specimen UCS against w', where trends through average UCS values for each cement content have been added for clarity. Figure 3 shows similar behaviour for all tested cement contents, in that maximum UCS values are, within the scatter of the data, largely obtained by materials com-

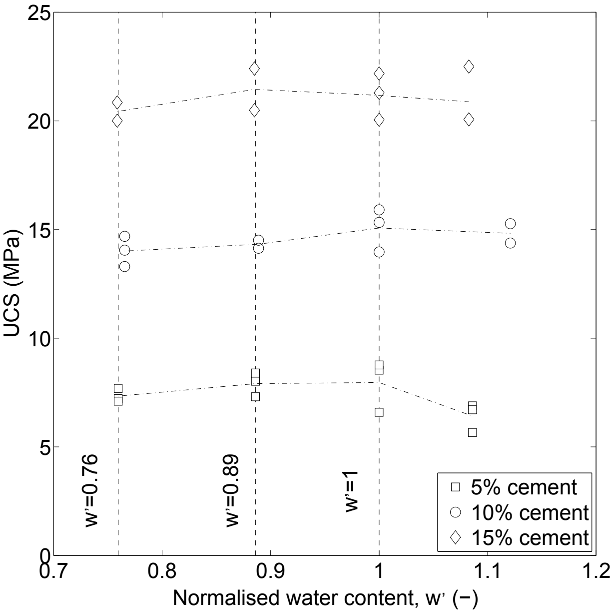

Figure 3: UCS results for specimens compacted at controlled values of w'

pacted between $w' = 0.89$ and $w' = 1$. This is consistent with findings of Beckett and Ciancio 2014. Differences between maximum and minimum strengths in Figure 3 per given mix are also of similar magnitude to those found in that work (roughly 2MPa). Relationships between w' and mix strengths are shown in greater detail in Figure 4, where specimen UCS has been normalised via UCS' $= {}^{\mathrm{UCS}}/_{\overline{\mathrm{UCS}_{\max}}}$ and where $\overline{\mathrm{UCS}_{\max}}$ is the maximum average UCS found for that material.

Figure 3 shows that, with the exception of specimens manufactured at 5% cement content, specimens manufactured to the same ρ_d values above and below $w' = 1$ achieved roughly identical strengths, seemingly contradicting results found in Beckett and Ciancio (2014). This is investigated in more detail in Figure 5, which shows changes in specimen ρ_d between 0 (white markers) at 28 days (black markers) due to cement gel growth. Note that ρ_d values at compaction shown in Figure 5 are lower than the target values shown in Figure 2; this is due to the need to trim specimens once compacted to achieve a smooth testing surface.

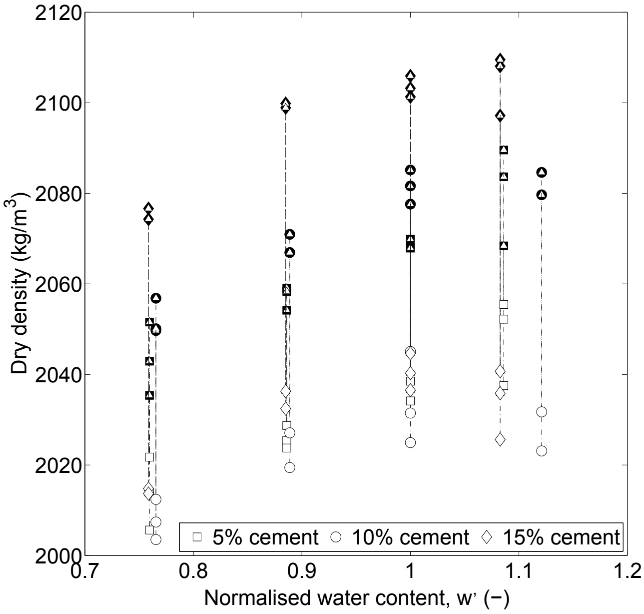

Figure 5: Evolution of specimen dry densities. White markers: ρ_d at compaction; black markers: ρ_d at 28 days. Arrows show transition between 0 and 28 days.

For all values of w', Figure 5 shows significantly larger increases in ρ_d for specimens manufactured at higher cement contents; this is to be expected, due to the larger volume of cement gel created. However, larger changes in ρ_d are seen for $w' > 1$ than for $w' = 0.89$, despite their similar densities. This is consistent with Beckett and Ciancio 2014 and suggests that greater amounts of hydrated cement were present in specimens compacted $w' > 1$ than for those at $w' = 0.89$. An exception to this is again seen for 5% cement specimens made at $w' > 1$. However, Figure 5 shows that compacted ρ_d values for 5% specimens manufactured at $w' = 0.89$ were lower than those compacted at $w' > 1$. Notably, the latter specimens achieved the lowest value of UCS of all tested specimens, despite their apparent 'advantage' of a higher compacted density. It is suggested that, for $w' > 1$ 5% specimens, higher values of ρ_d resulted in a reduced cement gel interconnectivity, due to the reduced porosity, and hence lower strengths. If results corresponding to $w' > 1$ for 5% cement are discounted from Figure 4 (circled), a relatively consistent trend is seen between all cement contents, with strengths peaking as $w' \to 1$ and reducing thereafter, as identified above.

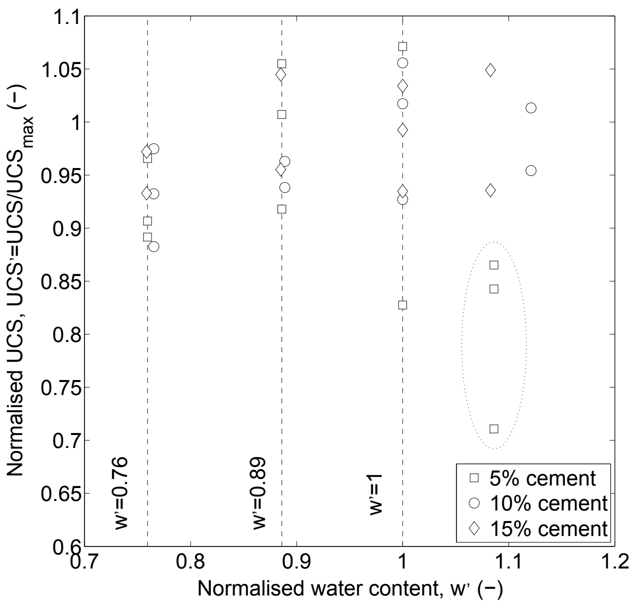

Figure 4: Normalised UCS results

It is well known that the water-cement ratio (w/c) is a key factor in controlling the strength of concrete mixtures (Neville 2011). Given the similarity in their

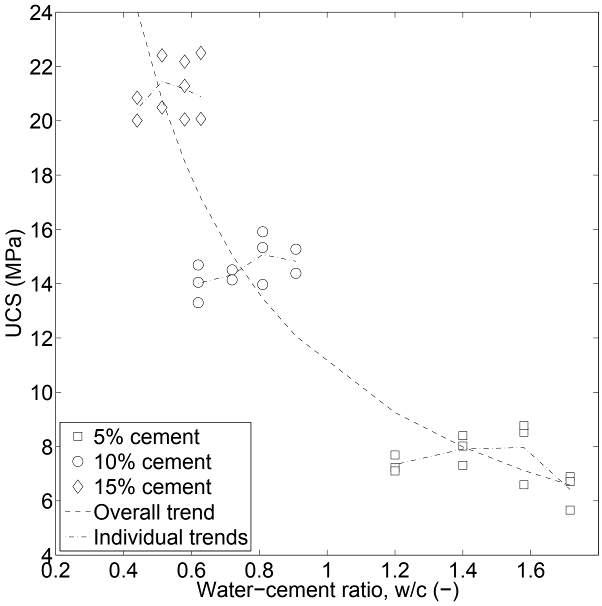

Figure 6: Specimen UCS vs water-cement ratio showing polynomial fit to data and individual material trends (from Figure 3)

components, it has therefore been suggested that w/c plays a similarly important role in CSRE materials (Ciancio, Jaquin, & Walker 2013).

Specimen w/c against UCS are shown in Figure 6. Though results in Figure 6 across all tested materials suggest that a decrease in w/c results in an increase in strength, as is the case for concrete, the outcome that strength increases with cement content is largely trivial. Interestingly, however, results in Figure 6 show no apparent relation between w/c and UCS for constant cement contents, i.e. no increase in strength is observed when w/c reduces through a reduction in w'. This is illustrated in Figure 6 by results found for $w' = 0.76$ for 10% cement and $w' \geq 1$ for 15% cement; although the two materials achieved very different strengths, their w/c values are equal. A similar result was found by Fernandes et al. 2007 for compacted clay-sand-cement mixes. In that work, a strong trend between UCS and w/c was found for mixtures compacted at or above $w' = 1$, with UCS rapidly decreasing for mixtures compacted below their OWC. It is therefore clear that microstructural phenomena regarding the distribution of the cement and soil aggregates play a key role in determining material strengths beyond a simple ratio between water and cement. An explanation might be that, in concrete, all of the water in the mixture (with the exception of that lost to evaporation) is available for cement hydration by virtue of its fluidic, saturated nature (Neville 2011). In CSRE, however, there is competition for water between the cement and the dry soil. Evidence for such a mechanism is suggested in Beckett and Ciancio 2014, however testing was not conducted over a range of cement contents. This is therefore a subject for further testing; microstructural investigations using SEM are ongoing.

4 CONCLUSIONS

This paper has presented experimental work investigating the role of compaction water content in controlling cementation mechanisms present in CSRE materials. Results showed similar trends in strength between specimens compacted to specific values of w' at different cement contents, demonstrating the strong role played by particle aggregation in strength development in CSRE. Material w/c were also investigated, showing that these alone are insufficient to describe cementation mechanisms in CSRE, suggestibly due to the different hydration environments between CSRE and concrete for which w/c was originally derived.

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